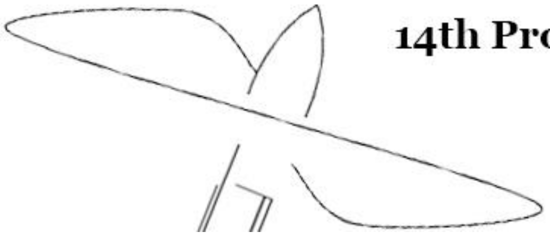

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CNC MACHINING OF PROPELLERS TO BETTER THAN CLASS S TOLERANCES

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CNC MACHINING OF PROPELLERS TO BETTER THAN CLASS S TOLERANCES

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Abstract

Producing class S propellers and water jet impellers presents serious challenges for propeller manufacturers. To overcome these challenges and consistently manufacture propellers with superior quality, an integrated approach was adopted when developing and implementing a process for Computer Numerically Controlled (CNC) machining of propeller surfaces. Highlights of this process are: (1) CNC machining of all blade surfaces; extreme surface blending, (2) CNC machining to final form & finish without hand grinding and (3) high precision, better than class S. This paper will describe various challenges encountered in the production of CP propeller blades and how these challenges were overcome in order to produce accurate CP propeller blades which exceed class S tolerances.

INTRODUCTION

Computer Numerically Controlled (CNC) machining of propeller blades was pioneered in the 1970's by KaMeWa (AB Karlstad Mekaniska Werstads) in Sweden and in the1980's by the Bird Johnson Company (now Rolls-Royce Naval Marine) in Walpole Mass. Papers by Donald E. Ridley (1) and by Mark F. Nittel (2) give a comprehensive overview of the implementation of a blade machining facility in Walpole Mass. During the last 20 – 25 years CNC milling machines have been generally accepted as the preferred way of machining of propellers and propeller blades. Even with this wide acceptance of CNC machining technique, producing a propeller or a propeller blade with class S tolerances remains a challenge.

Class S tolerances are the tightest tolerances in ISO 484/1 (3) and ISO 484/2 (4) manufacturing standards for propellers. Propellers meeting class S tolerances represented the best that propeller manufacturers could achieve in the 20th century within the prices that governments would pay for quiet naval propellers. The demand for quiet propellers has grown with the cruise ship business and Dominis anticipates that the desire for even quieter propellers will grow too. Dominis also believes that with advances in manufacturing and enhancements in the production process, propellers made to better than class S tolerances could be produced for about the same price. Therefore, let us see then what type of manufacturing process would guarantee production of propellers with precision exceeding class S tolerances.

When developing this new process, all aspects of the existing manufacturing processes which can potentially influence the precision of the end result were re-assessed. Possible improvements were identified, and benefits of these improvements were evaluated and implemented. The following enhancements to the propeller manufacturing process were implemented: propeller surface representation, fixturing, tooling and CNC tool path generation.

Hand grinding of residual scallops left by milling cutters on propeller blade surfaces was assessed as an important source of variability and inconsistencies in finish machined propeller surfaces. Therefore, hand grinding was eliminated from the propeller manufacturing process.

The ultimate goal of this new propeller manufacturing process is CNC machining of all propeller blade surfaces in such a way that after the propeller blade is removed from the milling machine, there is no need for any additional hand finishing. In other words, if the surface geometry and roughness specified by propeller designer was met by the CNC programs without additional hand finishing steps, then it can be said that propeller blade was CNC machined to *"final form and finish"* (7).

This paper will describe the various challenges and successes in implementing this new propeller manufacturing process for CNC machining of Controllable Pitch (CP) propeller blades. This protocol was used with great success in the production of several sets of CP propeller blades for the Halifax Class Canadian Patrol Frigates (CPF) program and CP blades for USCG 210 foot cutters.

MACHINING TO FINAL FORM AND FINISH

We use the following descriptive definition for *"final form and finish"*: *final form* of a propeller is defined by the propeller's table of off-sets and/or by its CAD solid model, while *finish* is the desired final surface roughness of the propeller. We are typically asked to meet tolerances of a particular propeller class as specified by ISO 484/1 and ISO 484/2.

We feel that the final form of a propeller surface is best achieved by CNC machining of the CP propeller blade in a vertical position. Precision of the surface geometry depends on several factors:

1, Precision of machining fixture
2, Blade bending due to stress relieving of propeller blade casting
3, Blade bending due to machining forces
4, Cutter wear

Precision of the machining fixture is of paramount importance and no effort should be spared in achieving flatness of the bolting surface and perpendicularity of dowel holes used for locating and pinning the propeller blade casting on the fixture. In our experience the effects of stress relieving during rough machining are minimal if the propeller blade is machined in several surface bands where the pressure side of the band is machined immediately after the suction side of the band. During finish machining, blade bending due to machining forces is negligible. Cutter wear could play a role only during finish machining. However when machining Ni-Al-bronze propeller blades we have not experienced major problems with cutter wear.

The cost of CNC machining is highly dependent on the surface roughness required, so we include some detail on roughness here. Surface roughness is a function of scallop height left after CNC machining. For a spherical cutter of radius **r,** distance between cuts (step over) being **s,** scallop height **ε** also known as **R_t** (peak to valley roughness) can be approximated as **$\varepsilon = s^2/8r$** (Fig. 1). **R_a** (arithmetic average roughness) can be approximated as **$R_a = 0.032s^2/r$.** These approximations are valid when **$\varepsilon \ll r$.** For a derivation of this expression for surface roughness see Qu and Shih (5).

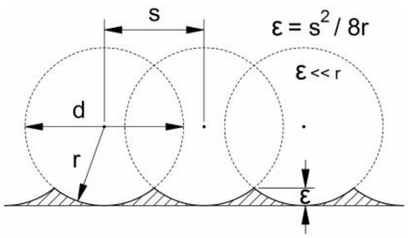

Fig. 1, Theoretical scallop height

Dominis' definition of when a propeller blade surface is machined to *"final form and finish"* is when both surface geometry and roughness exceed the requirement for class S propellers (Table 4) without hand finishing.

PROTOCOL FOR CNC MILLING OF PROPELLER BLADE SURFACES

When developing the protocol for CNC milling of propeller blade surfaces several important factors need to be considered before the implementation of the CNC programs. These are grouped into two areas:

1, Selection of the milling cutters
2, Selection of the milling process

1. Selection of the milling cutters

The residual scallop height left by a cutting tool is a function of both the material properties of the casting being machined and the cutting tool chosen. However, for the purposes of this discussion, we will consider only the theoretical scallop height defined in Fig. 1 as **$\varepsilon = s^2/8r$** and the theoretical arithmetic average roughness defined as **R_a** = **$0.032s^2/r$.** **R_a** will be used to select suitable milling cutters and parameters to be used for CNC milling of propeller blade surfaces to achieve *"final form and finish"*.

After extensive experimentation and testing of ball nose cutters of different types and diameters, cutters suitable for rough and finish milling operations of propeller blade surfaces were selected (see Table 1).

Table 1. **ε** and R_a for given cutter dia. and step over

		Rough milling	Finish milling
Cutter diameter, d,	inch	2	1.25
Step over, s,	inch	0.197	0.025
Scallop height, **ε**,	inch	0.0048	0.00012
Surface roughness R_a,	µinch	1240	31

From Table 1 it can be seen that the target surface roughness required for class S propellers can be exceeded by using a 1.25 inch diameter ball nose cutter. Using the 1.25" dia. ball nose cutter with a step over of 0.625 mm (0.025 inch) will in theory produce a surface finish (R_a**)** of approximately 31 µinch. Since the formulae that we are using for computation of theoretical scallop height **ε** and theoretical average surface roughness R_a are approximations, the actual surface roughness after CNC milling will probably be of poorer quality and R_a somewhat greater than 31 µinch. The measurement of the surface roughness after milling will confirm the actual surface roughness obtained by the CNC protocol implemented during manufacturing. The ball nose cutter selected for finish milling has a single round, center cutting, carbide insert with two cutting edges. Inserts for this cutter are precision ground with tolerance of ±0.00025 inch on the radius.

Selection of depth of cut for rough milling and finish milling will be affected by the amount and distribution of extra material on the casting. The extra material on the propeller blade casting has to be removed first by rough milling and then by finish milling. Ideally, there should be only one roughing and one finishing pass. However, if there is a substantial amount of extra material on the casting or if extra material on the casting is not evenly distributed, more than one roughing pass will have to be applied in order to bring the rough milled surface down to the ideal amount of extra material for the finishing pass.

What is the ideal amount of extra material to be removed during finish milling pass? Testing of 1.25 inch diameter ball nose cutter under different milling scenarios has shown that excellent results in terms of surface finish and speed of milling can be achieved with depths of cut between 0.060 inch and 0.080 inch (1.5 mm to 2 mm). The 1.25" in dia. ball nose cutter was used at feed rates up to 6 m/min. When tested, the following parameters were used: rpm = 6285, depth of cut 0.060 inch, width of cut of 0.025 inch. The milling machine used for testing has a spindle with a maximum rotational speed of 8000 rpm, with a maximum programmable feed rate of 6 m/min and rapid return rate of 10 m/min. Therefore, any combinations of feed rate and speed which exceed 6 m/min could not be tested and evaluated. The milling machine was thus the limiting factor for the speed of finish milling.

2. Selection of the milling process

Direction of CNC milling was chosen to always be in the direction of climb milling. Consequently the cutter will be in the air during the return trajectory to the starting point of the next cut step. Milling during the return travel was briefly considered and rejected as the cut produced by return milling was of inferior quality to the cut produced by climb milling.

Selection of the geometry of the tool path is critical to the quality of the CNC protocol. Radial section, horizontal and vertical tool path trajectories were considered. Of these we have selected radial section cuts for CNC milling of the pressure side (PS) and the suction side (SS) propeller blade surfaces. This seemed the most logical approach since both the PS and the SS surfaces of propeller blades are defined at radial sections. The CAD surfaces used for creation of tool paths are created from radial sections which are defined by the table of off-sets and pitch, rake and skew distributions.

Since leading and trailing edges are defined at the same radial sections which define the PS and SS surfaces, leading edge (LE), trailing edge (TE) and anti-singing chamfer will be CNC milled in the same tool path as the PS and the SS of the propeller blade.

All propeller blade surfaces were to be CNC milled to + 0.020" dimension of target. This 0.5 mm, evenly distributed, extra thickness per side will increase propeller blade lifespan by providing additional material for future polishing during regular propeller cleaning and maintenance cycles.

The tip of the propeller blade (from r/R = 0.975) was machined with a smaller step-over between cuts in order to reduce the scallop heights there at the leading and trailing edges.

MANUFACTURING PROCESS FOR CNC MACHINING OF CP PROPELLER BLADES

Machining of CP propeller blades is most conveniently done on a horizontal milling machine. For illustration purposes, a CNC propeller manufacturing process shall be described which was developed for machining of CP propeller blades for the Halifax Class Canadian Patrol Frigates (CPF). The manufacturing process for CPF propeller blades consists of four distinct operations:

1, Rough milling of the trunnion;
2, Rough milling of blade, fillet and palm surfaces;
3, Finish milling of blade, fillet and palm surfaces, and
4, Finish milling of the trunnion

The propeller blade trunnion is machined with the propeller blade casting mounted and secured in a special fixture which holds the propeller blade in a horizontal orientation providing unhindered access to the propeller blade foot and overhang. Trunnion OD, blade overhang if any, trunnion seal surfaces, dowel holes, bolt holes and counter bores are machined while the propeller blade is in its horizontal orientation. Propeller blade surfaces, fillets and palm are machined with the propeller blade bolted and pinned in the vertical orientation on a fixture attached to the horizontal rotary table of the milling machine.

Operation 1: Rough milling of the trunnion

Rough milling of the trunnion (Fig. 2) is an operation which consists of standard shop activities such as drilling, taping, facing and boring. However, facing of the trunnion bottom (the blade reference plane) surface and boring of dowel holes, two features which are used for locating and securing the blade on the vertical fixture, must be done with maximum care and accuracy. Precision of the propeller blade surfaces depends on the flatness of the blade reference plane, perpendicularity of dowel holes to the blade reference plane and precision of dowel hole locations on the trunnion. It is also important to note that the reference plane surface, dowel holes and the trunnion OD will at this stage be finish machined to a known plus dimension.

The back-counterboring of the trunnion bolt holes presents additional challenges. This task requires special tools which have been custom designed and manufactured by Dominis Engineering.

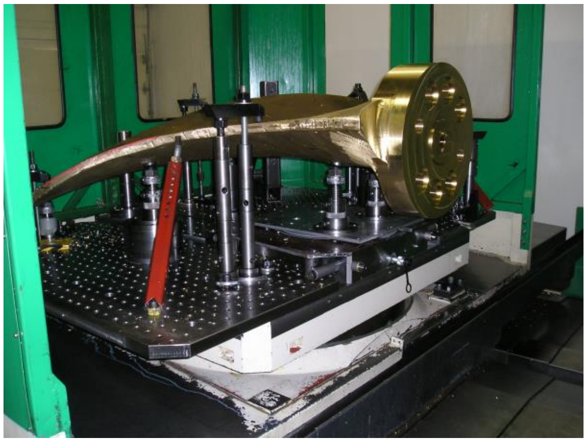

Fig. 2, Rough milling of the trunnion

Fig. 3, Rough milling of the blade surfaces

Operation 2: Rough milling of blade, fillet and palm surfaces

The rough milling of blade surfaces (Fig. 3) consists of 4 distinct tasks:

a) Rough milling of the blade contour using a 3 inch dia. shell mill cutter;
b) Rough milling of PS and SS surfaces using a 2 inch dia. ball nose cutter;
c) Rough milling of the palm using a 4 inch dia. button mill cutter, and
d) Rough milling of fillets using a 2 inch dia. ball nose cutter.

All blade surfaces were rough milled with 5 mm step-over. All rough milling of radial sections is done using climb milling with cuts starting at the TE and ending at the LE, or vice versa depending on blade side and blade orientation.

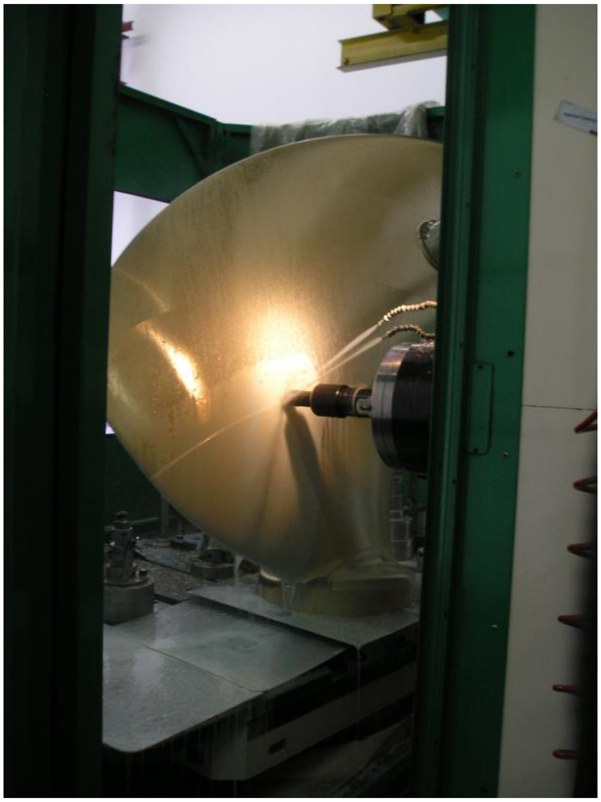

Fig. 4, Finish milling of blade surfaces

Operation 3: Finish milling of blade, fillet and palm surfaces

Finish milling of blade surfaces (Fig. 4) consists of 3 distinct tasks:

a) Finish milling of PS and SS surfaces using a 1.25 inch dia. ball nose cutter
b) Finish milling of the palm using a 4 inch dia. button mill cutter and
c) Finish milling of fillets using 0.75 inch and 1.0 inch dia. ball nose cutters.

All ball nose cutters used for surface finishing tasks have single, center cutting, carbide insert with two cutting edges. Inserts for these ball nose cutters are precision ground to a tolerance of ± 0.00025". The protocol for finish milling is the same as for rough milling. The only difference is the diameter of the cutter (1.25 in) and step-over (0.625 mm). All finish milling of radial sections is done using climb milling, with cuts starting at the TE and ending at the LE, or vice versa depending on blade side and blade orientation.

Operation 4: Finish milling of the trunnion

Finish milling of the trunnion (Fig. 5) consists of several finishing tasks such as:

a) Finish boring of trunnion bolt holes;
b) Finish milling of counter bores;
c) Finish boring of dowel holes;
d) Finish boring of the trunnion OD, and
e) Finish boring and facing of all seal surfaces on the trunnion.

Proper execution of these finishing tasks is crucial since tolerances for all seal surfaces are very tight.

Fig. 5, Finish machining of the blade trunnion

TOOL PATH GENERATION

Since the LE and TE will be machined at the same time as the PS and SS surfaces, the entire propeller blade from tip to fillet can be milled with only two CNC program strategies: one for PS and one for SS. However, before any CNC programming can be undertaken, the geometry of the propeller blade has to be thoroughly verified. The areas on the propeller blade which demand particular attention are:

1. The propeller blade tip;
2. The geometry of the anti-singing edge;
3. The continuity between leading and trailing edges and PS and SS surfaces, and
4. The continuity between blade, fillet and palm surfaces.

The verification process of the propeller blade geometry depends on the form and format in which the propeller blade geometry is supplied by the client:

a) A 2D table of off-sets and pitch, rake and skew distributions, or
b) A 3D CAD model.

The geometry of all propeller blades discussed in this paper was defined by (a) a 2D table of off-sets and pitch, rake and skew distributions. The CPF propeller blades were defined with 2D sections from 0.3 r/R to 0.9875 r/R (12 sections). Each section is defined by 16 stations from 0.5% to 95% of chord, LE and TE radii, tip radius and location and geometry of anti-singing chamfer. PS surface and SS surface of the propeller blade were defined by a total of only 192 points (12 sections x 16 stations). Using this sparse set of data points supplied by the client, a complete 3D geometry of propeller blade suitable for CNC milling to *"final form and finish"* had to be created.

Qualitatively speaking, propeller blade surfaces should be smooth; there should be no discontinuities, no inflexion points, no steps between surface patches and no bumps on the surface. Quantitatively speaking the process must achieve an average arithmetic roughness $\mathbf{R_a}$ of 118 µinch by CNC milling only.

Smoothing of propeller blade sections

As the first step in data preparation, all 2D sections specified in the table of offsets supplied by the client have to be verified and curves, which include leading and trailing edges, must be constructed for each radius. These 2D curves then have to be checked for smoothness and presence of bumps and discontinuities. Figure 6 shows a sample section as supplied by the client with curvatures computed at the original points. Note that the curvatures are not gradually increasing towards the leading edge and also note that there is an inflexion in the curve between points 4 and 6. Figure 7 shows "updated" sample section with curvatures computed at locations of old and new points; note also that curvatures of the section are gradually increasing as they should towards the LE; and also note that a bump in Fig. 6 was smoothed out in Fig. 7. The net result is that an inflexion point was eliminated and that two points were added in order to ensure that the desired form of the leading edge is maintained. Figure 8 shows the corrected section data over-laid over the original data. All manipulations and adjustments of the given section are done in order to create a smooth 2D curve which will later be transformed into a smooth 3D curve on the propeller blade surface. Smoothing and cleaning of 2D propeller sections is a time consuming process, but it has to be done in order to verify and confirm smoothness of the starting data.

After the original 2D sections are verified, one can proceed with the construction of additional 2D sections between those specified in the original table of offsets and the construction of 2D sections for the definition of the propeller blade tip. All new 2D sections also have to be tested for continuity and smoothness using the same techniques described in the paragraph above. Continuity and smoothness have to also be checked between adjacent sections and across the entire propeller blade surface. The process of creating additional 2D propeller sections has to continue until the total number of 2D sections created is sufficient for the definition of smooth 3D propeller surfaces. Once a sufficient number of 2D sections has been created, one can proceed with the computation of 3D propeller sections. This data will be used to create a 3D model of the propeller blade.

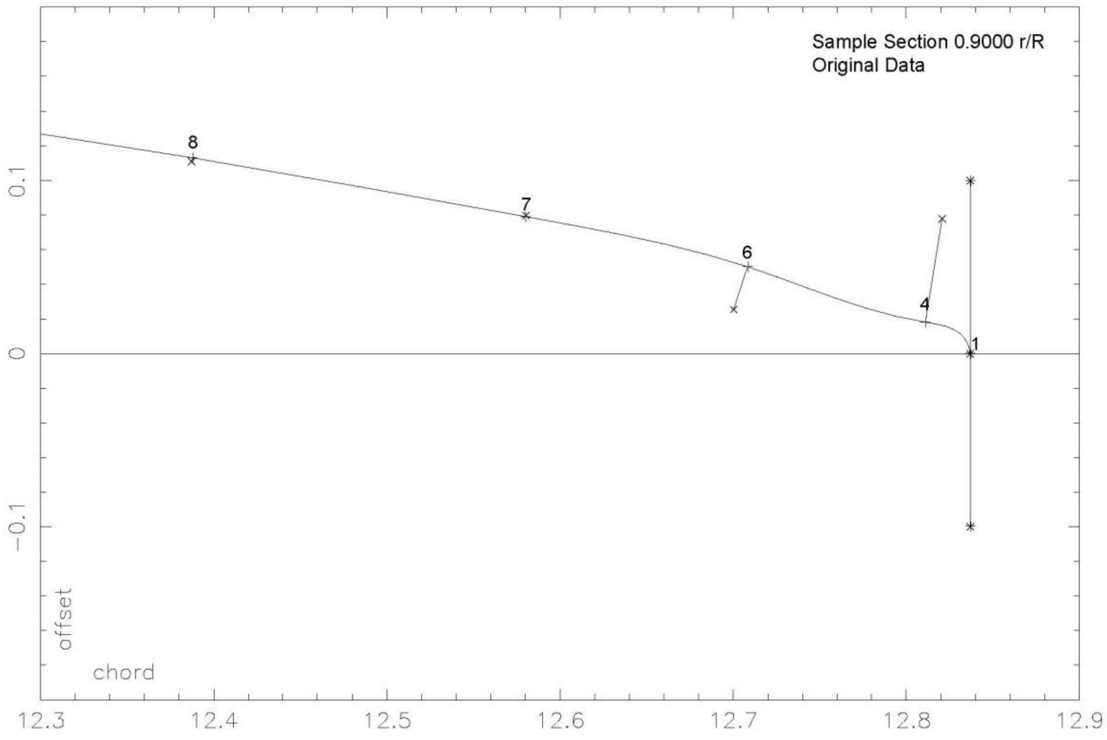

Fig. 6, Original data before smoothing

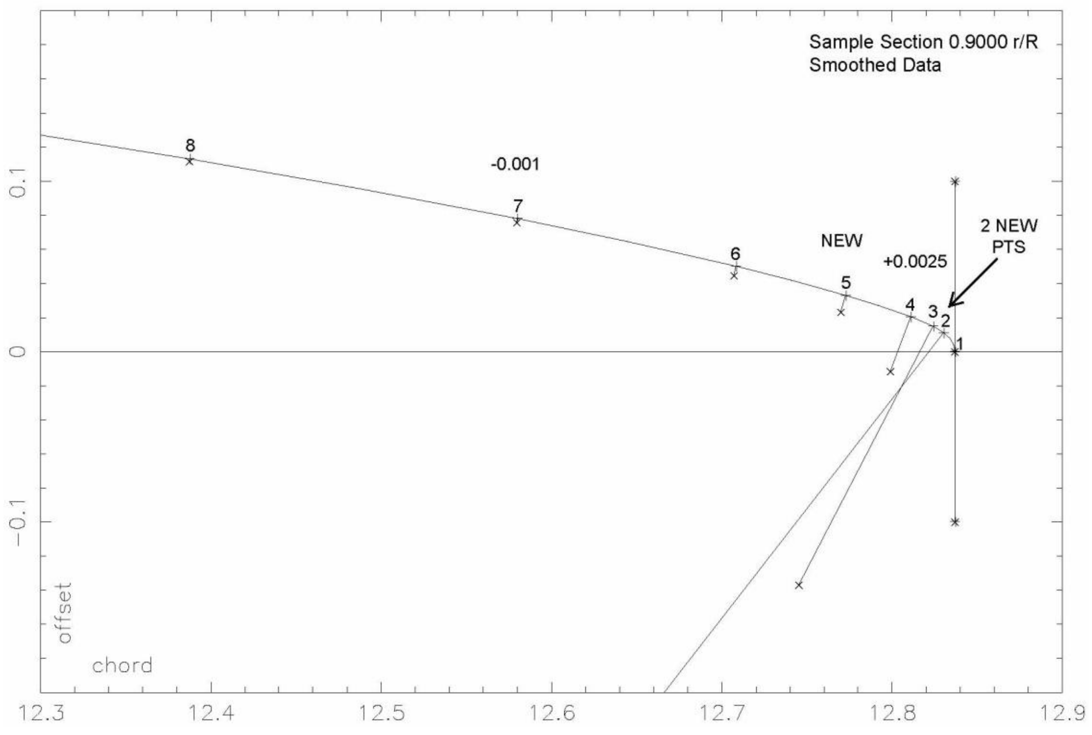

Fig. 7, Data after smoothing

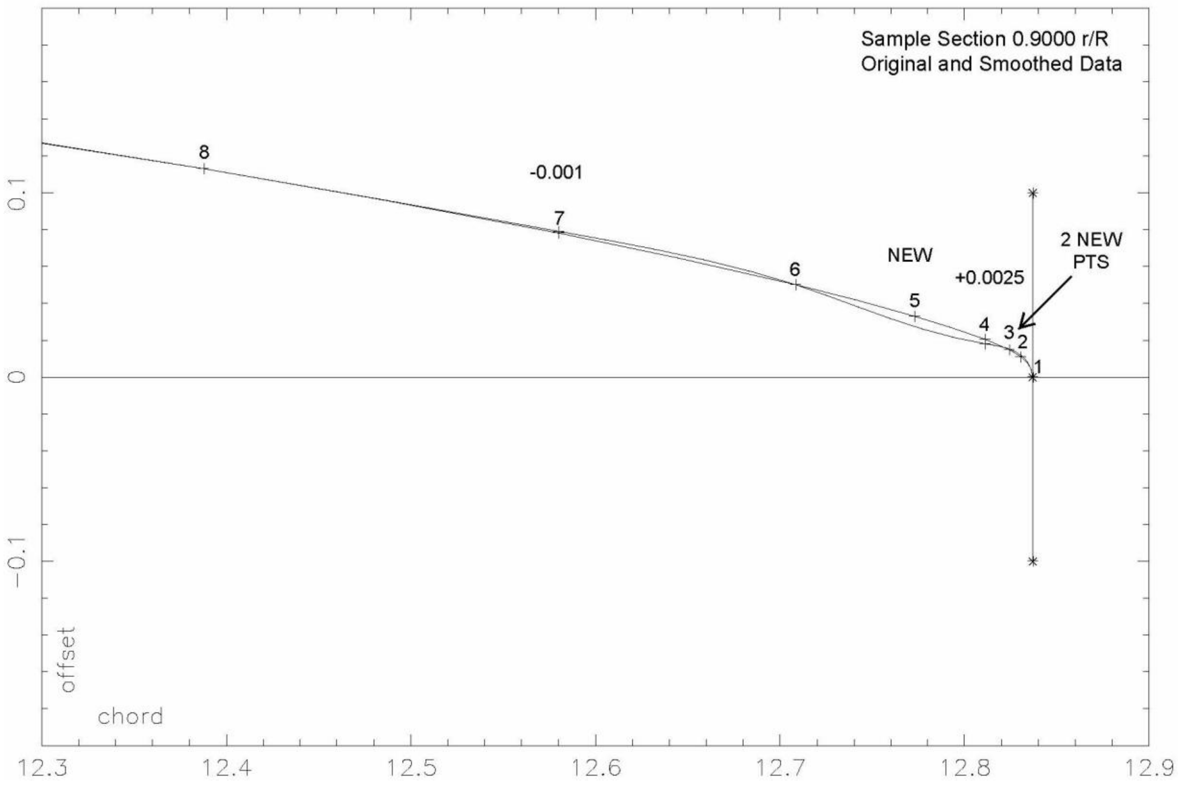

Fig. 8, Original and smoothed data

Creating a good, smooth 3D model of a propeller blade which is suitable for CNC milling to *"final form and finish"* is a time consuming iterative process. The protocol to attain target smoothness of propeller blade surfaces can assume no compromises with the quality of the propeller blade surface. Using commercial CAD software systems to perform smoothing calculations on 2D curves described graphically by Figures 6-8 proved unpredictable. To solve this problem we developed DGCAD in-house, a CAD package for the manipulation of 2D splines. DGCAD offers the CAD operator a comprehensive set of commands for creating, editing, translating, scaling, manipulation and smoothing of 2D splines. This CAD package has been an indispensable tool for creating and smoothing of both 2D blade sections and 3D propeller blade surfaces.

CNC programming

We can proceed to CNC programming only after a smooth 3D model of the propeller blade has been created. CNC programs for machining of trunnions were created using commercially available software packages: MasterCAM and HyperMill. Machining of the trunnion is a challenging process due to the precision of the seal surfaces however this is beyond the scope of this paper. Therefore, only the programming strategies for CNC milling of blade surfaces will be discussed here.

PS and SS surfaces for CPF blade are physically large. The propeller blade has a span of 1.6 m, an average chord length of 1.4 m and a surface area per side of 2.2 sq. m. In order to make CNC programs manageable in size and executable run time, PS and SS surfaces are divided into 5 bands of approximately 15 inches along the blade span. The propeller blade is milled starting with band 1 at the propeller tip. Leading and trailing edges are milled integral to the PS and SS blade surfaces. As stated earlier, all cuts are along the radial sections of the blade. The SS surface of one band is milled immediately after the PS side of that band is completed. Band 2 is milled after band 1 and so on until band 5. Before the milling of each band, the propeller blade is rotated by an average pitch angle for that band in order to minimize tool length and to bring all regions of the band to roughly the same distance from the spindle face.

The actual CNC milling programs are generated using the DGCAM software package. DGCAM was developed in-house in order to facilitate generation of large CNC programs required for CNC milling to *"final form and finish"*. Input to DGCAM are data representing surfaces and splines generated by the DGCAD software and the parameters of the milling protocol, i.e. serial numbers of the first and the last radial sections, depth of cut, step-over, milling cutter diameter, milling parameters etc. Except for minor differences in the first and the last radial section to be cut for each band, rough milling and finish milling programs are machining the same surface bands using different cutters, different depth of cut and different step overs. Milling parameters for rough milling and finish milling are given in Table 2. After the CNC programs are created they are processed by the DGPOST_R16 post processor software which prepares NC code for the milling machine to be used for milling of the propeller blade. Before CNC programs can be allowed to run on the milling machine, they have to be verified under full machine simulation using the VERICUT software. CNC programs are verified while milling a model of the propeller blade casting mounted on the model of the actual machining fixture.

Table 2, Parameters for rough and finish milling

Milling parameters	Rough milling	Finish milling
Cutter diameter, inch	2	1.25
Step over, inch	0.197	0.025
Depth of cut, mm	6 – 8	1.5
Speed, rpm	3015	6285
Feed rate, m/min	1.2	6

CNC MILLING OF PROPELLER BLADES

The CPF propeller blades were CNC machined on a 4-axis horizontal boring milling machine with a working envelope of 2.5 m x 1.8 m x 1.4 m. This milling machine has an 8000 rpm spindle, programmable feed rate of up to 6 m/min and rapid travel of 10 m/min in X, Y, Z axes, a programmable (W-axis) quill 200 mm in dia. by 450 mm long and a rotary table of 6 ton capacity with a maximum rotational feed rate of 2 rpm. The controller of the machine has large look ahead buffer which, for a given curvature of the tool path, enables CNC milling with maximum feed rates and minimum following error. The milling machine is laser calibrated each year. Positional accuracy on all linear axes of the milling machine is in the order of ±0.004 mm.

Table 3, Rough and finish milling timing

Description	Rough milling		Finish milling	
	PS	SS	PS	SS
No. of cuts	340	340	2560	2560
Length of cuts, m	476	476	3584	3584
Cutting time, hours	7	7	12.8	12.8
Return time, hours	1.2	1.2	8.8	8.8
Total time, hours	8.2	8.2	21.6	21.6
Grand total time, hours	59.6			

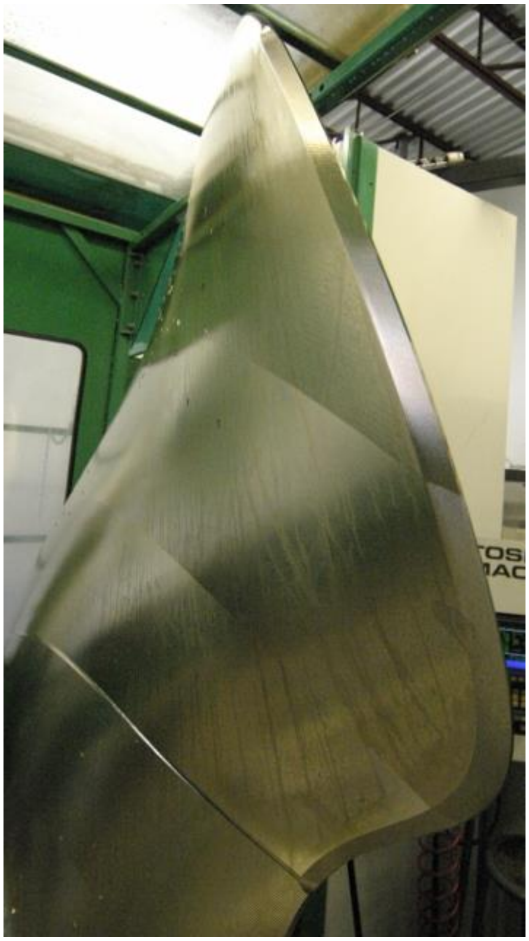

Fig. 9, Anti-singing chamfer finish machined with back surface. Bands 1, 2 and 3.

Details for milling tasks, including the time required to run complete rough and finish milling programmes for PS and SS surfaces are given in Table 3. For most of the propeller blade castings, with no more than 8-10 mm of extra material somewhat evenly distributed, rough and finish milling of CPF propeller blade surfaces was accomplished in 60 hours. Except for indexing of propeller blade from PS to SS after milling is completed for each band of propeller blade surfaces which has to be performed by an operator, the entire process is run unattended. Before finish milling programs could be run on a propeller blade, a sequence of special warm up programs for all axes has to be run for several hours so that the milling machine can reach its steady state temperature. Once started, finish milling programs run continuously until the end. Figure 9 shows a propeller blade where the first 3 surface bands, including the anti-singing edge of the propeller blade, are finish milled. Figure 10 shows the quality of rough milled and finish milled surfaces on the propeller blade.

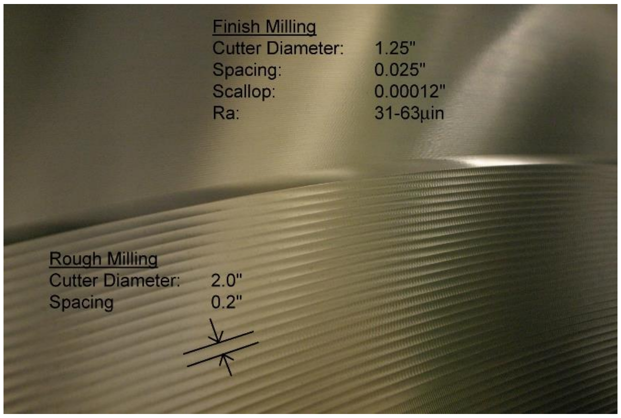

Fig. 10, Rough milled and finish milled surfaces as they appear after milling.

MEASUREMENT OF PROPELLER BLADES

Measurement of surface roughness

In all areas of the blade, except in the region of the leading edge, measured surface roughness was between 31 and 63 µinch (0.8 µm and 1.6 µm). In the region of the leading edge, surface roughness was around 63 µinch. All roughness was less than 118 µinch (3 µm). Therefore, we have achieved our objective of CNC machining a propeller blade to *“final form and finish”* with the surface roughness exceeding ISO 484/1 class S tolerances.

Methodology of blade measurements

Measurement of propeller blade surfaces was performed on the horizontal milling machine using an electronic touch probe. Outfitted with a touch probe, the horizontal milling machine essentially becomes a very accurate coordinate measuring machine. The milling machine is always recalibrated before it is used as a measuring device. A Renishaw touch probe (Fig. 11) was modified with the installation of a special sleeve adapter restricting the movements of the stylus only to Z-direction (Fig. 13). The touch probe is outfitted with a pointed stylus (Fig. 12).

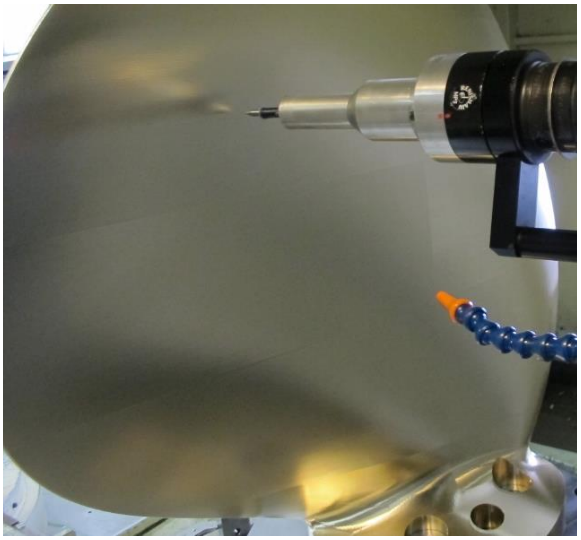

Fig. 11, Electronic touch probe for measurement of blade surface points

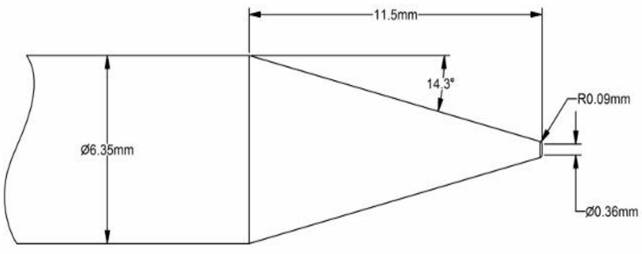

Fig. 12, Touch probe stylus tip

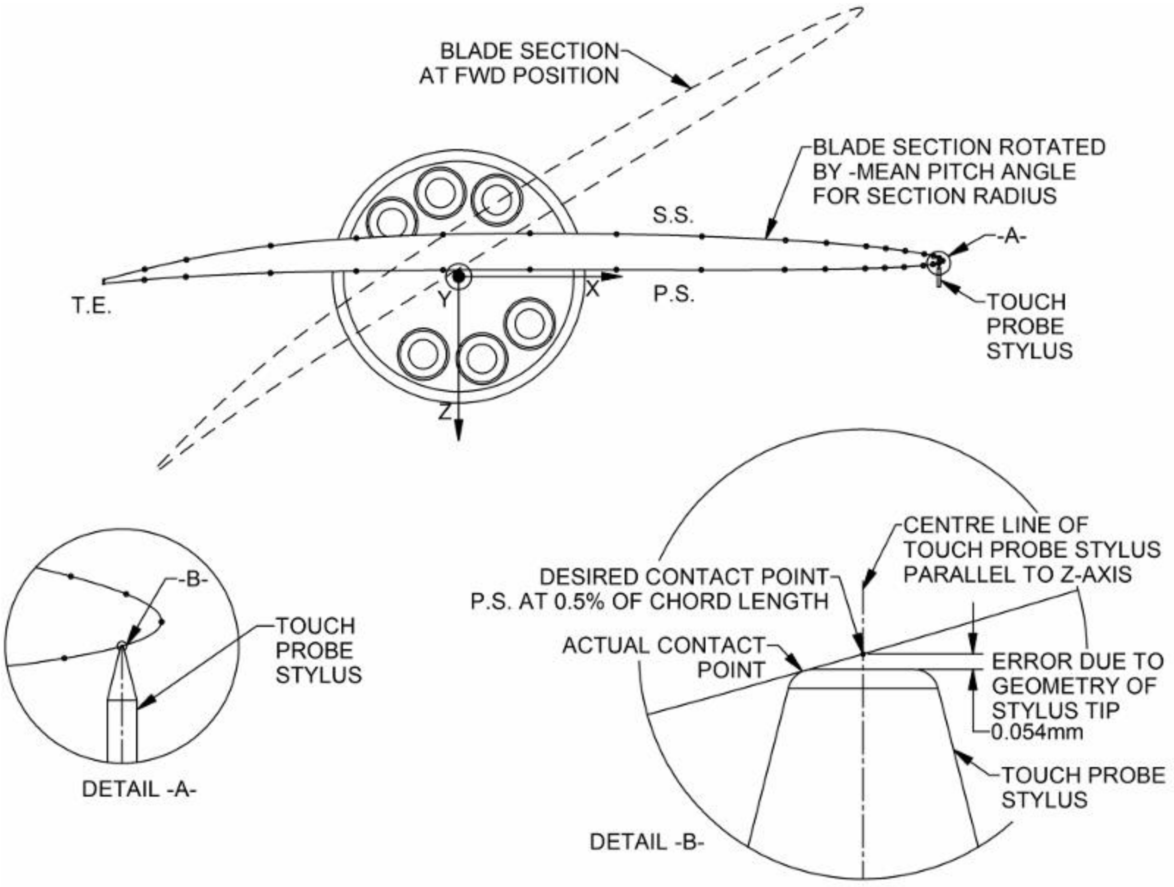

Fig. 13, Measurement of radial sections

Each radial section of the blade is measured when the blade is rotated by the pitch angle of that section (Fig. 13). This is done in order to minimize measurement errors and to orient the touch probe stylus as close as it is practical to the normal of the surface point being measured. Measurement errors due to the curvature of the surface will be largest close to the leading edge. The error due to the geometry of the stylus tip, when measuring station at 0.5% of chord on section 0.7 r/R, is estimated to be 0.054mm or 0.0014 inch (Fig. 13, detail A and B)

The touch probe movement is controlled by the CNC program to positions on the propeller blade which correspond to stations at given blade radius specified in the table of offsets. All 3D touch probe measurements are converted by a computer program into a set of 2D coordinates which can be compared to coordinates in the table of off-sets of the propeller blade.

Measurements of the length of propeller blade radial sections are performed using a manually operated edge finder (Fig. 14 - 15). Measurements are performed with the propeller blade rotated by the pitch angle of the section being measured. Coordinates of the center of the edge finder are computed so that the edge finder touches the blade contour perpendicular to the intersection of the radial section and trailing edge on one end of the blade and radial section and leading edge on the other end of the blade. Depending on the position and location of the propeller blade contour, the operator manually moves the edge finder towards the blade edge either along the X-axis or along the Y-axis until contact is made with the blade contour. Coordinates of the center of the edge finder are then used for computation of the coordinates on the propeller blade contour (Fig. 16)

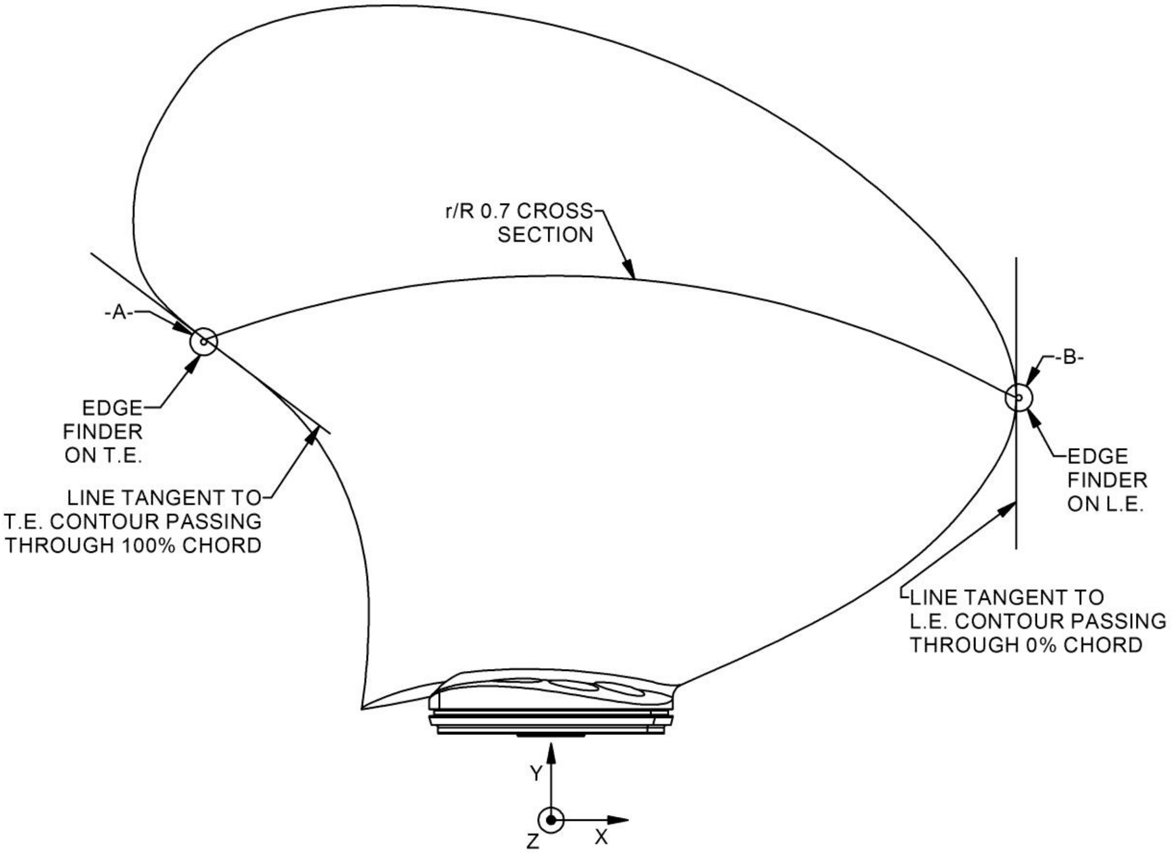

Fig. 14, Measurement of the length of blades section (front view)

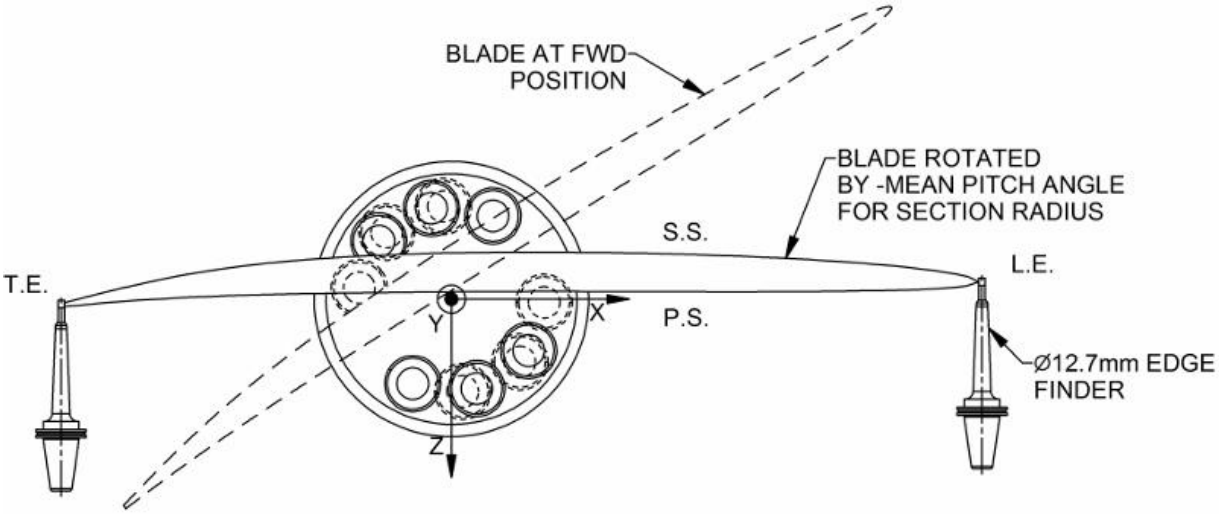

Fig. 15, Measurement of the length of blade section (top view)

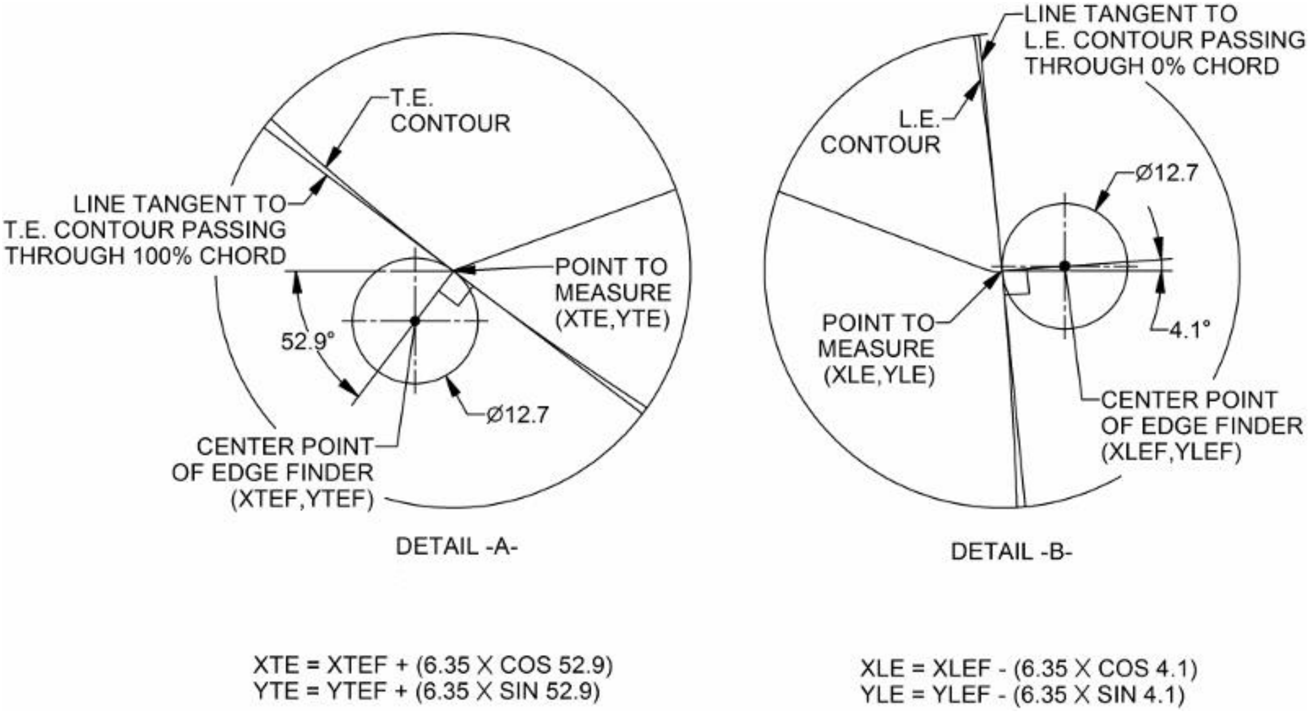

Fig. 16, Measurement of the length of blade section (detail)

Using the CNC operated electronic touch probe and manually operated edge finder, 10 RH and 10 LH propeller blades fabricated for the CPF program were measured. 3D measurements obtained by the touch probe were the basis for computation of 2D coordinates corresponding to pressure side and suction side points in the table of offsets. From the table of offsets containing measured data we computed thickness, local pitch, mean pitch at each radius and blade pitch. From the measurements obtained with the manually operated edge finder, chord length for each propeller blade section was computed.

Leading and trailing edges were measured along the radial sections using ROMER arm touch probe. For each edge region, 25 points were measured on PS and 25 points on suction side. 3D edge measurements were placed over solid model data of the propeller blades and deviations from the model were measured graphically.

Tolerances for propeller manufacturing

Manufacturing tolerances for propellers greater than 2.5 m in diameter are governed by the international standard, ISO 484/1. Summary of six key tolerances required which need to be measured for acceptance purposes of propellers meeting class S requirements are given in Table 4.

Table 4, Class S tolerances per ISO 484

Measured propeller blade parameter	ISO 484/1 Propellers of diameter greater than 2.5 m
	Tolerances for class S
Surface roughness, $\mathbf{R_a}$	less than 3 μ metre
Thickness	+ 2 %, max. of 2 mm - 1 %, min. of -1 mm
Chord length	± 1.5%, min. of 7 mm
Local pitch	± 1.5%
Mean pitch of each radius	± 1.0%
Mean pitch per blade	± 0.75%

Evaluation of measurements

Measurements for 10 RH and 10 LH propeller blades were analysed and deviations of measured values from design values were computed for seven key propeller blade parameters:

1. Face (pressure side) coordinates
2. Back (suction side) coordinates
3. Thickness
4. Chord length
5. Local pitch
6. Mean pitch at each radius
7. Blade pitch

The ISO standard does not provide explicit tolerances for coordinates on the face and back of the propeller blades. However, measurements of coordinates on propeller blade surfaces are used for the computation of other propeller parameters. Deviations between measured and design coordinates on the face and the back of all 20 propeller blades were computed and distributions of these deviations are presented here in Figs. 17 and 18, to give a complete picture of the performance and accuracies achieved by CNC machining to *"final form and finish*". Deviations between measured values and design targets for thickness, chord length and pitch are also computed and their distributions presented here in Figs. 19 to 23. Distributions of deviations for each of the 7 propeller parameters measured are presented side by side for RH and LH blades (Figs. 17 to 23). Table 5 contains the summary of precisions achieved and compares them with ISO 484/1 class S tolerances.

Deviations between measured coordinates and target coordinates in the regions of leading and trailing edges were computed to be ± 0.300 mm (± 0.012 inch). This deviation compares favorably with the deviations for surface points on the pressure and suction sides and is considerably better than the ISO 484/1 class S tolerance which is: ± 0.5 mm (± 0.020 inch).

All surface points are accurate to ± 0.012 inch for a total sample of 4360 measured points. Given the accuracy of all surface points we are confident that extreme radius, skew and rake were well within ISO 484/1 class S tolerances.

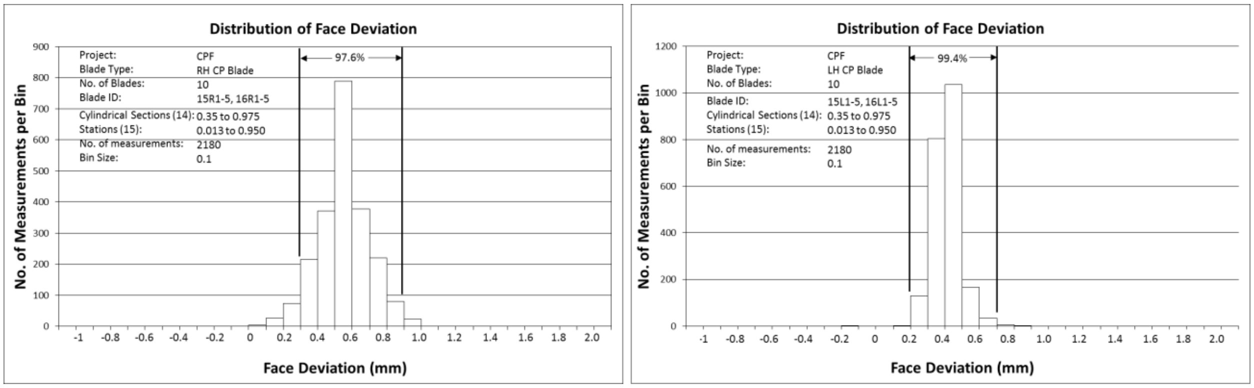

Fig. 17, Distributions of face deviations for RH and LH propeller blades

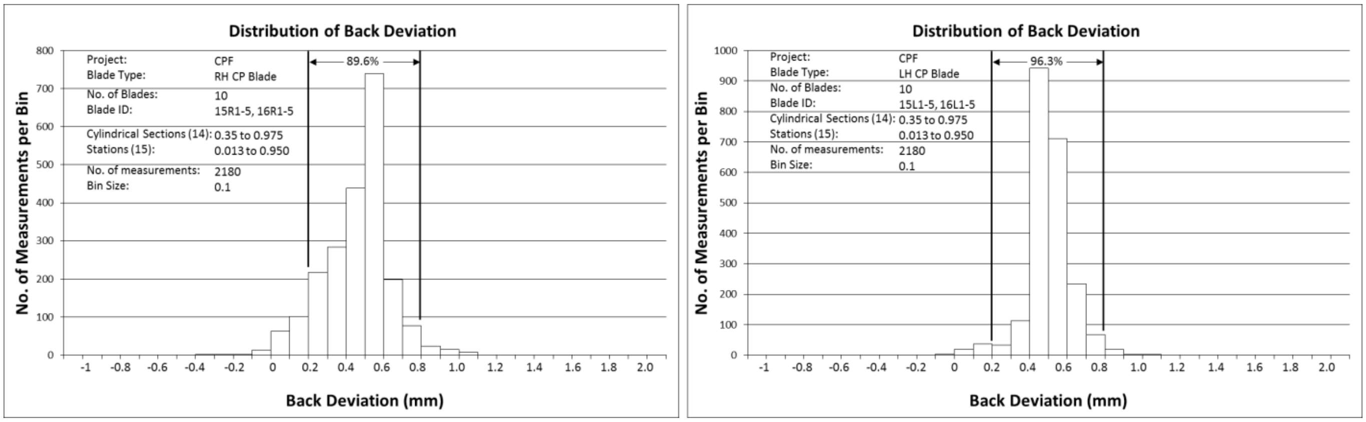

Fig. 18, Distributions of back deviations for RH and LH propeller blades

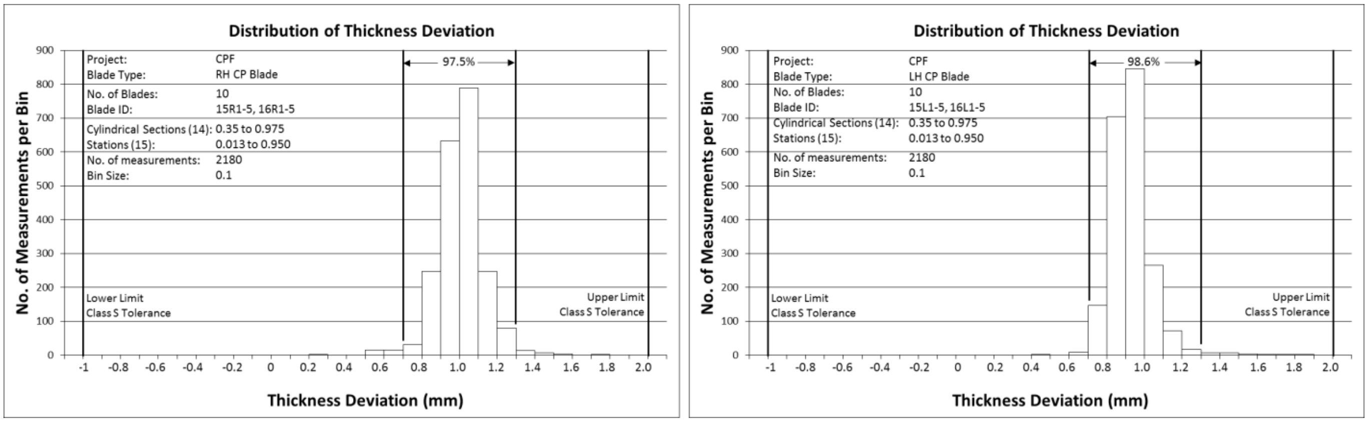

Fig. 19, Distributions of thickness deviations for RH and LH propeller blades

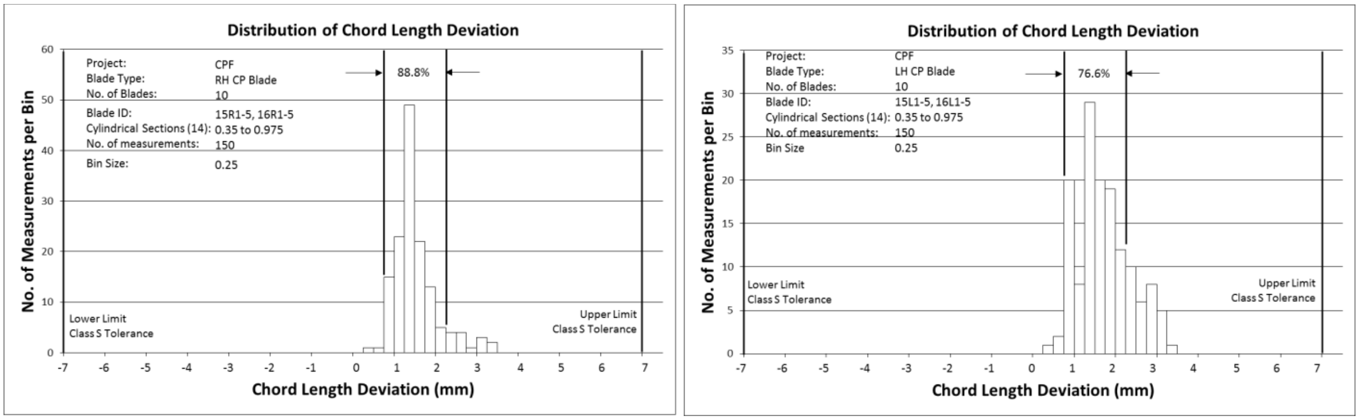

Fig. 20, Distributions of chord length deviations for RH and LH propeller blades

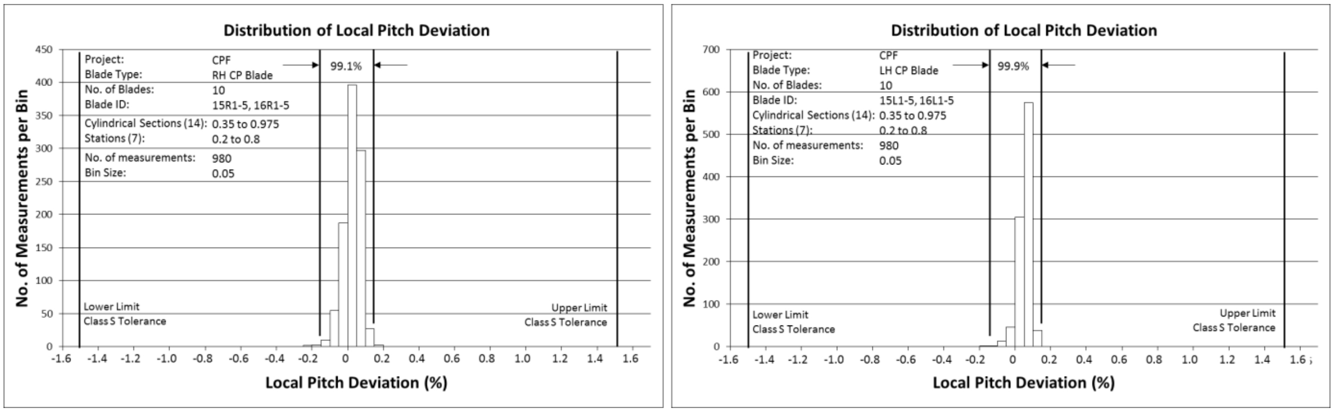

Fig. 21, Distributions of local pitch deviations for RH and LH propeller blades

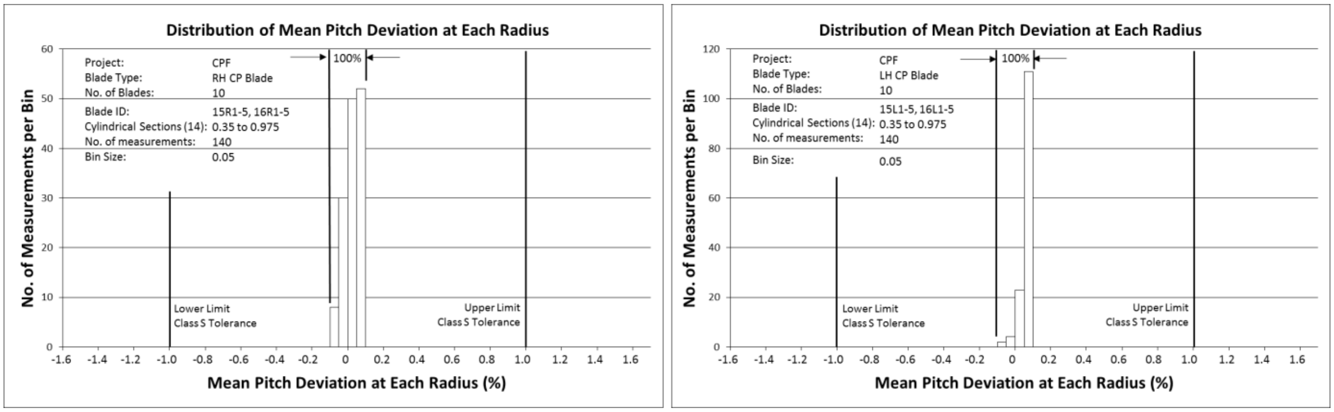

Fig. 22, Distributions of mean pitch deviations for RH and LH propeller blades

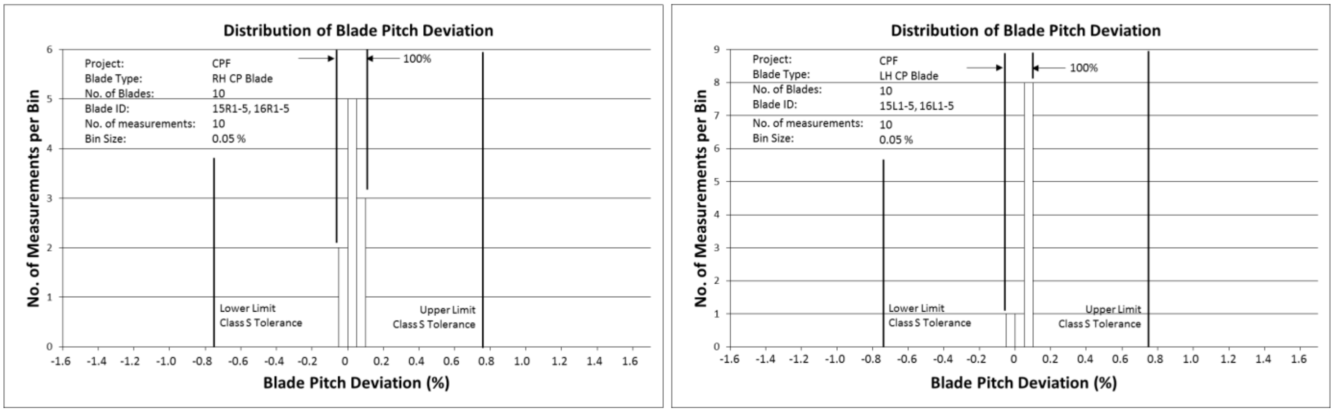

Fig. 23, Distributions of blade pitch deviations for RH and LH propeller blades

Table 5: Analysis of measurements

Measured parameter	No. of Blades	No. of measurements	Precision achieved	ISO class S requirements
Coordinates on face	10 RH	2180	97.6% of points measured are within ±0.300 mm of the target dimension of +0.5 mm from design coordinate	Not required
	10 LH	2180	99.4% of points measured are within ±0.300 mm of the target dimension of +0.5 mm from design coordinate	Not required
Coordinates on back	10 RH	2180	89.6% of points measured are within ±0.300 mm of the target dimension of +0.5 mm from design coordinate	Not required
	10 LH	2180	96.3% of points measured are within ±0.300 mm of the target dimension of +0.5 mm from design coordinate	Not required
Thickness	10 RH	2180	97.5 % of all thicknesses are within ±0.300 mm of the target dimension of +1.0 mm form design dimension.	Exceeded
	10 LH	2180	98.6 % of all thicknesses are within ±0.300 mm of the target dimension of +1.0 mm form design dimension.	Exceeded
Chord length	10 RH	150	88.8 % of all chord lengths are within +1 mm and +0.5 mm of the target dimension of +1.0 mm form design dimension.	Exceeded
	10 LH	150	76.6 % of all chord lengths are within +1 mm and +0.5 mm of the target dimension of +1.0 mm form design dimension.	Exceeded
Local pitch	10 RH	980	99.1% of local pitch measurements are within less than ±0.2% from design dimension	Exceeded
	10 LH	980	99.9% of local pitch measurements are within less than ±0.2% from design dimension	Exceeded
Mean pitch	10 RH	140	All mean pitch measurements are within less than ±0.15% from design dimension	Exceeded
	10 LH	140	All mean pitch measurements are within less than ±0.15% from design dimension	Exceeded
Blade pitch	10 RH	10	All blade pitch measurements are within less than ±0.1% from design dimension	Exceeded
	10 LH	10	All blade pitch measurements are within less than ±0.1% from design dimension	Exceeded

CONCLUSIONS AND FUTURE DEVELOPMENT

10 LH and 10 RH propeller blades have been fabricated at Dominis Engineering for the CPF program using CNC machining *to "final form and finish"*.

A fabrication protocol has been developed for this program, in order to meet ISO 484/1 class S tolerances.

High precision measurements on the final form and finish of the 10 LH and 10 RH propeller blade surfaces using seven independent parameters has yielded a gauge for the tolerances attained with this fabrication protocol.

It has been demonstrated that the developed CNC fabrication protocol yielded 20 propeller blades fabricated to an exceptional accuracy, which is better than ISO 484/1 class S tolerances.

Propeller blades which are CNC machined to *"final form and finish"* have, besides the exceptional accuracy demonstrated, the additional advantage of excellent blade to blade repeatability which effectively eliminates balancing adjustments. Elimination of the hand finishing step from the propeller manufacturing process gives the propeller designer exactly what he needs and results in cost-cutting measures for the manufacturer.

Future development efforts are directed towards speeding up the process of clean-up and smoothing of input propeller blade data and reducing rough and finish milling times by developing new tooling for high speed milling.

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